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ON THE INFLUENCE OF MATERIAL PROPERTIES IN SHEET BENDING PROCESSES

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Abstract. In order to achieve the high performance and precision requirements of modern sheet bending processes, an appropriate implementation of material properties is essential. Experiments have shown that even variations within a lot of a specific material play an important role. For this sake, detailed knowledge of the influence of the specific properties like flow curve, rolling direction, strain rate, anisotropy etc. is required. In a first step, tension tests have been performed for some materials which are frequently used in industrial applications. In order to simulate the sheet bending process, advanced simulation models have been implemented. Detailed parameter studies have been performed, and the essential parameters and their influence on the bending process have been found out. The results have been compared to measurement results of the bending process.

1 INTRODUCTION

High performance and precision is required in modern sheet bending processes, cf. Kunze et al. [1]. In modern automatic panel benders, one piece work flow production is expected with extremely small tolerances of the product. On the other hand, the material properties vary with respect to the specific sheet material type. Nowadays, even variations within a lot of a specific material play an increasing roll. In order to achieve the high precision demands, advanced simulation models are required that consider the essential material properties, cf. Hammelmüller et al [2]. Additionally, adaptive methods are necessary, such that the panel bender automatically reacts to material variations.

In this contribution, the influence of material parameters is studied, such as Young's modulus, the flow-curve and anisotropy. For this sake, the bending process has been modelled by two-dimensional finite elements as shown in [2]. Tension tests have been performed for some industrially important materials, and the measured data has been implemented in the Finite Element model. Then efficient parameter studies have been performed to find out the influence of the material parameters on bending forces and bending angle. The simulation results are verified by measurements performed on a Salvagnini P4Xe automatic panel bender, see www.salvagnini.com for further information.

With these investigations, a more detailed understanding of the bending process is obtained which enables a further improvement of the manufacturing process.

2 MODEL OF THE BENDING PROCESS

The principle of the bending process is shown in Figure 1. The sheet metal is clamped with the upper and lower clamping tool and the sheet is formed with the moving bending tool. The thickness of the sheet is denoted by s (max. 3.2 mm). The maximum sheet width (direction out of the plane) is 3850 mm. The dimensions of the formed profile are given by the angle φ (max 135° after springback), the side length are denoted by a and b, and the radius r. As pointed out by Kunze et al. [1], very small tolerances are required for these parameters in modern industrial manufacturing processes.

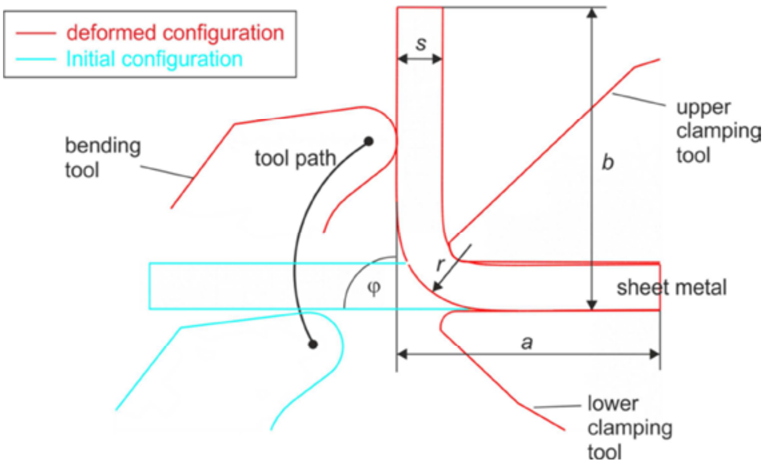

Figure 1: Principle of the bending process

An overview of the implemented simulation models has been given by Hammelmüller et al. [2]. Due the large ratio of length and width, the two-dimensional Finite Element Model based on plane strain elements turned out to be appropriate in order to investigate the influence of material parameters on the bending process.

3 MATERIAL BEHAVIOR

Frequently used materials in industry are steel alloys (mild steel, high tension steel, stainless steel) and aluminium alloys. Recently, the use of high tension steel has increased. Thus, several types of high tension steel (provided by voestalpine STAHL GmbH, www.voestalpine.com/stahl) are considered in this paper.

Figure 2 shows the results of the performed tension tests for three types of high tension steel. The nominal stress σ_{nom} is shown as a function of the nominal strain ε_{nom},

$$\sigma_{nom} = F/A_0, \qquad \varepsilon_{nom}=(L-L_0)/L_0, \tag{1}$$

where A_0 is the initial cross sectional area of the sample, L_0 the initial length. F and L are the measured force and length during the tension test. The results for higher strains, where significant necking of the cross-section in the tension test occurs, are not shown in Figure 2, because such necking behavior has not been observed in the considered bending process.

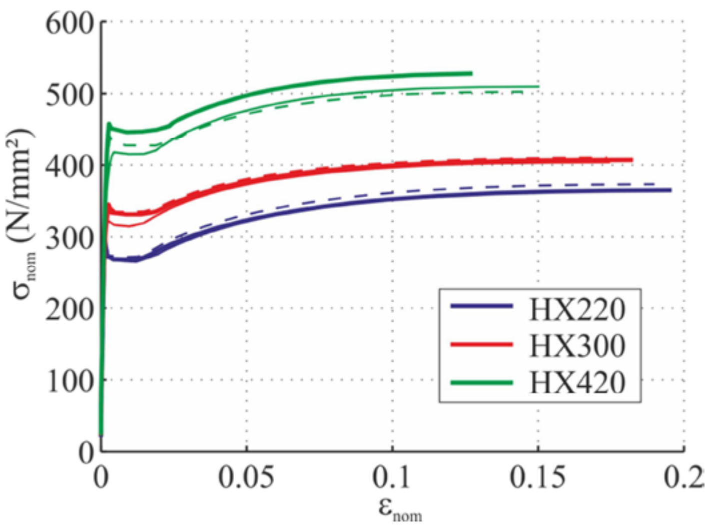

Figure 2: Results of tension test for three materials

In order to get information about the anisotropic behavior, the tension tests have been performed for samples that were cut out in three directions from the plane metal sheet in three directions, i.e. longitudinal, transversal and diagonal (45°) to the rolling direction. The directions are characterized by the line style in Figure 2. Additionally, the Lankford's *r*-values are measured in the tension tests, cf. Chen and Han [3]. The measured material properties are listed in Table 1.

As another important effect, Figure 2 shows a significant flow range: At the beginning of the tension test, the material behavior is linear elastic (Hooke's law). After reaching the yield strength, the nominal stress decreases. For nominal strains higher than about 0.02 (Lüders strain), the stress-strain-curve takes an exponential form. In the following we spend focus to the inelastic behavior of the material.

Table 1: Measured material properties

		yield strength (N/mm²)	tensile strength (N/mm²)	Lankford's coefficient (for 6% strain)
HX 220	0°	270.5	366.1	1.39
	45°	271.5	373.3	1.39
	90°	269.1	365.0	1.79
HX 300	0°	321.6	404.1	0.86
	45°	344.1	410.2	1.02
	90°	335.1	407.1	1.27
HX 420	0°	412.7	510	0.57
	45°	432.5	502.8	1.09
	90°	450.0	528.1	0.89

Nominal stress and strain are the results of standard tension tests because these quantities are easily computed from the measurement results. For the simulation of the bending process, the derivation of the flow curve is required, i.e. the true (Cauchy) stress $\sigma = F/A$ as a function of the logarithmic (natural) strain $\varepsilon = \ln(L/L_0)$, where A is the deformed cross-section during the tension test. From the results of the tension tests, we can set

$$\sigma = \sigma_{nom}(1+\varepsilon_{nom}), \qquad \varepsilon = \ln(1+\varepsilon_{nom}), \tag{2}$$

see Hill [4] or Lubliner [5].

Figure 3 shows the true stress as a function of the logarithmic strain. The thin grey curves show the results obtained from the measured data, the colored curves show exponential regressions for strains higher than the Lüders strain. The figures shows, that the exponential regression is a very good approximation for high strains. It satisfies the Ludwik equation [6],

$$\sigma = C\,\varepsilon^n, \tag{3}$$

where C and n are material constants, n is denoted as work-hardening exponent, cf [5].

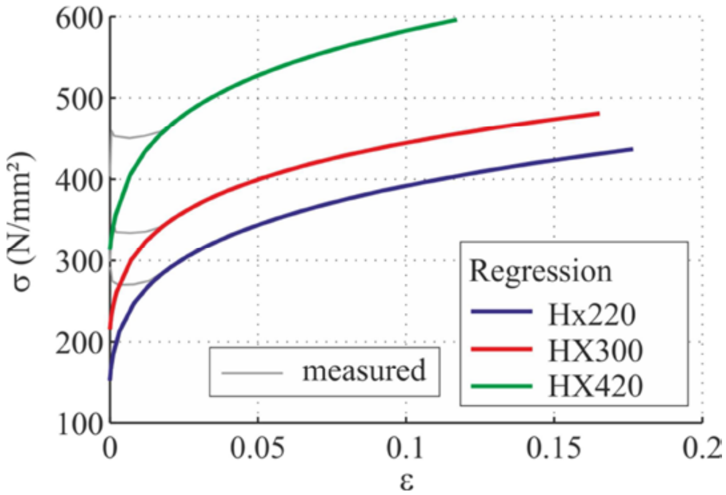

Figure 3: Results of tension test for three materials

4 SIMULATION AND MEASUREMENT RESULTS

In this section, the results of Finite Element Simulations with the material properties in section 3 are compared to measurement results. The simulations have been performed with the plane strain Finite Element Model as described in [2]. The measurements have been performed on a Salvagnini P4Xe automatic panel bender.

Two effects are studied in this chapter: In section 4.1 the influence of the flow range, and in section 4.2 the influence of anisotropy on bending force and bending angle is investigated.

4.1 Influence of the flow range

Figure 4 shows the results of the Finite Element computations for the bending force, i.e. the contact force between bending tool and the bent sheet metal. For each of the above mentioned three materials, three types of material laws have been implemented:

- Case 1: The flowcurve from the tension tests (grey curves in Figure 3). After reaching the uniform elongation, stress is kept constant (saturation). The results for the bending force is shown with grey color in Figure 4. Performing the simulations it has turned out that instability may occur, if the stress decreases too much after reaching the yield stress.

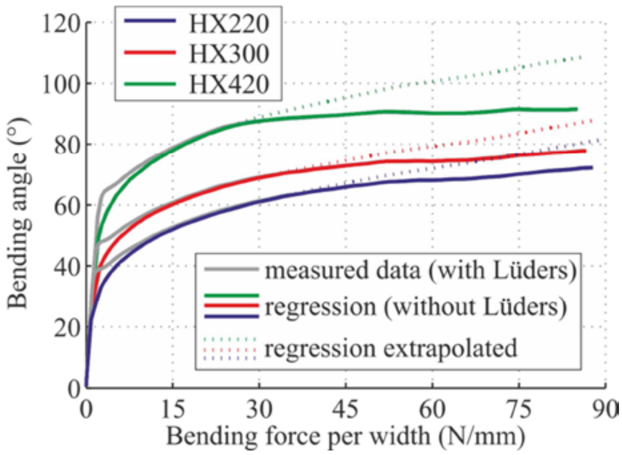

Figure 4: Results of the 2D-Finite Element Model

- Case 2: The Ludwik equation, Eq. (3), is implemented as shown in Figure 3 by colored lines. As for case 1, for strains larger than uniform elongation, stress is kept constant. The results for the bending force are represented by colored solid lines in Figure 4. A comparison to case 1 shows that the Ludwik approximation shows a very good coincidence for bending angles larger than 10°. For small bending angles, the influence of the flow range has to be modelled in more detail.
  For a maximum bending angle of about 90°, the results of the bending angle of case 1 and 2 differ of about 0.2°, if the same path of the bending tool is prescribed.
- Case 3: The Ludwik equation, Eq. (3), is extrapolated for strains larger than uniform elongation (up to very high values). The result is shown by dashed colored lines in Figure 4. The result coincides with case 2 up to an angle of 30-35°. Then case 2 shows a saturation of the bending force, while in case 3 the bending force increases.

4.2 Influence of anisotropy

In this section, the influence of anisotropy is investigated by comparing simulation and measurement results. For all bending processes the same path of the bending tool has been prescribed. The measurements have been performed with a sheet thickness of 1.5 mm and three values for the sheet width (500, 1250, 2500) mm. Because of statistical reasons, the measurements have been repeated several times. The progress of the bending angle could not be measured directly, such that it has been estimated by comparing the coordinates of the tool path in simulation and experiment.

Figure 5 shows the bending force for the investigated materials as a function of the bending angle. The measurement results are shown with thin dark blue lines in Figure 5. In the simulation model the Ludwik equation without saturation (case 3 in section 4.1) has been implemented. The red curve shows the results for isotropic material behavior, the light blue curve the results for anisotropy according to section 3. In the Finite Element model anisotropy is based on Hill’s yield criterion [4].

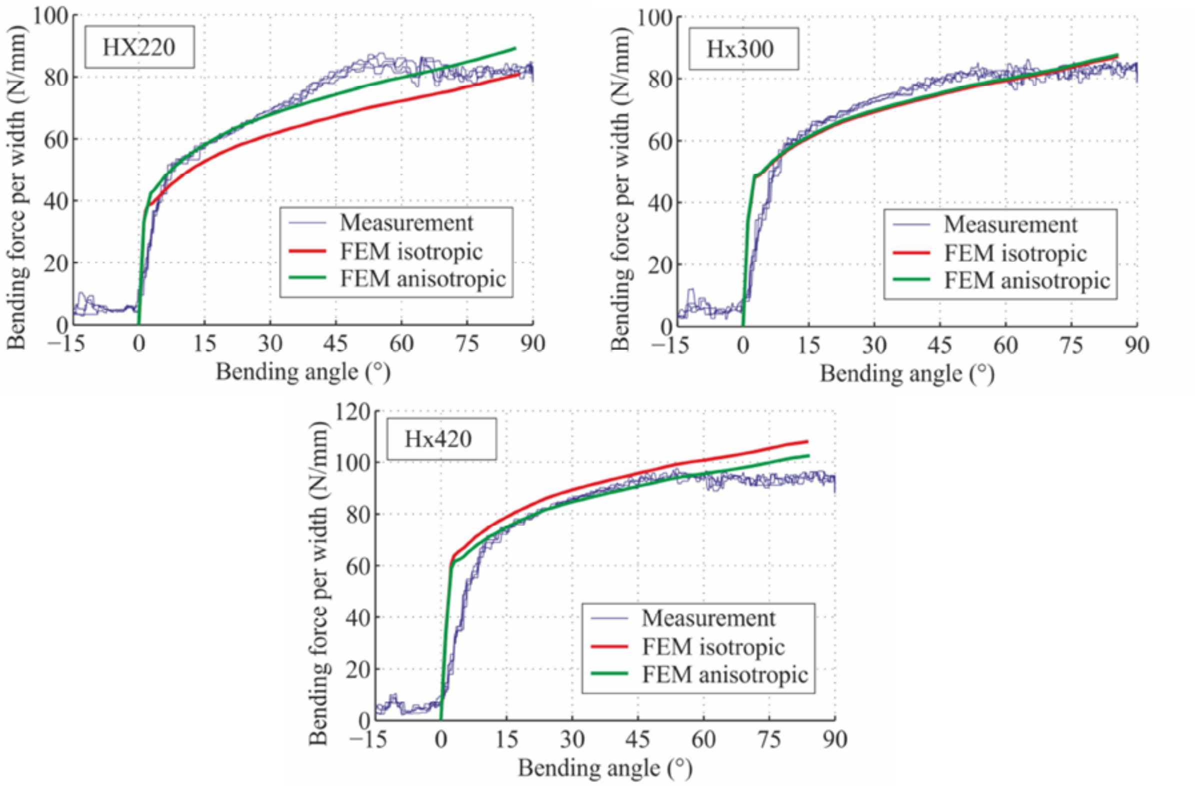

Figure 5: Influence of anisotropy on the bending force

The results in Figure 5 show that the coincidence between measurement and simulation is better, if anisotropy is considered. Anisotropy causes:

- HX220: an increase of the bending force
- HX300: no influence
- HX420: a decrease of the bending force

For the bending angle anisotropy causes

- HX220 : a decrease of the bending angle of about 1°
- HX300 : no influence
- HX420 : an increase of the bending angle of about 0.5°

Note that in high precision manufacturing processes the tolerances for the bending angle are below 0.5°. Thus, it is essential to correctly model the anisotropic material properties.

The measurement results in Figure 5 show another interesting behavior: For angles larger than about 50° the bending force shows a saturation. On the other hand, Figure 4 shows this behavior for the simulation results, where the flow curve has been defined up to uniform elongation (case 3). Recall that in the simulations the saturation of the force has started at an angle of about 35°. With these results it can be assumed that after reaching the end of uniform elongation, a further increase of the Cauchy stress occurs until an effective stress limit, where stress saturates. This is an interesting topic for further investigations.

5 SIMILARITY INVESTIGATIONS

A main advantage of the considered bending principle is the high versatility of the production process. By defining an appropriate tool path, very complex profile shapes can be produced by the Salvagnini machines. For a single bending process, the major geometric parameters are shown in Figure 6a, i.e. the sheet thickness s and the distance L which defines the start point of the tool path. One of two strategies can be chosen: (i) The bending tool rolls over the sheet, (ii) The tool remains on the first contact line (out of the plane Figure 6) on the sheet, i.e. there is a sliding contact.

As known from beam or plate theory the bending force is mainly dependent on s, L and the flow curve. Figure 6b shows 2D-FEM simulation results for the bending force of four material types with a large number of combinations of (s,L).

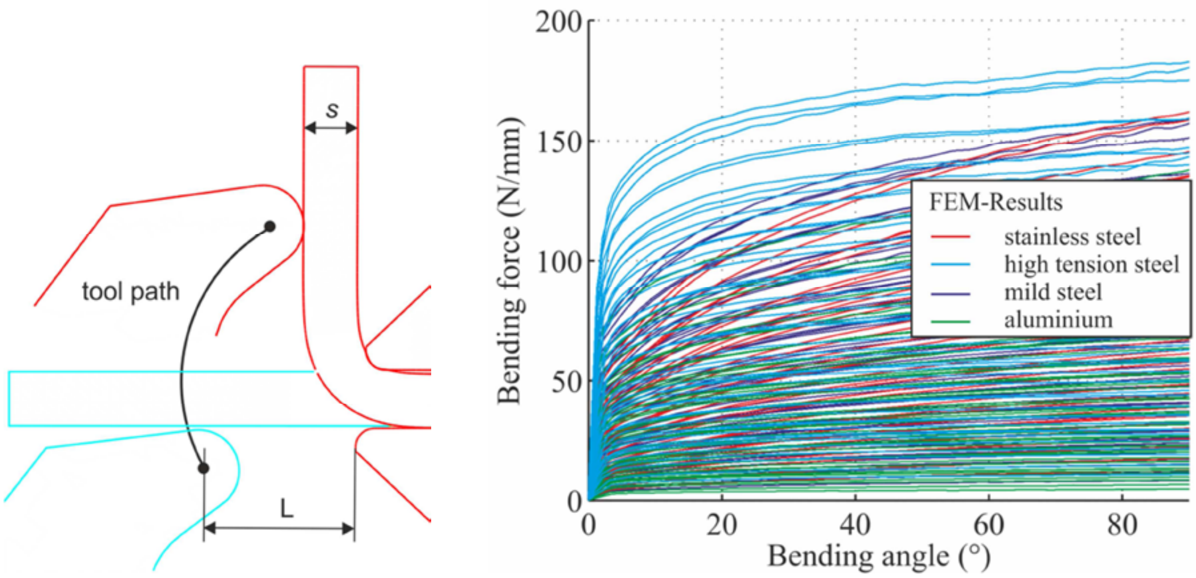

Figure 6: (a) Process parameters, (b) Bending force for four materials

Applying similarity methods, see e.g. Baker et al. [7], a scaled representation of the bending force has been found as shown in Figure 7. By an appropriate scaling dependent on *s* and *L*, several results for each material can be reduced to one curve. Thus, the scaled bending force only depends on material parameters, but is independent of the process parameters. In Figure 7, the grey curves show the scaled Finite Element results, the colored lines show an exponential regression.

Considering that the flow curve is also given in exponential form, i.e. the Ludwik equation, Eq. (3). The results show, that the scaled bending force as a function of the bending angle is mapped to the flow curve. This relation can be utilized for an identification of effective material parameters from measured bending forces. Due to the scaled formulation, the identification strategy can be applied for each parameter combination of *s* and *L*.

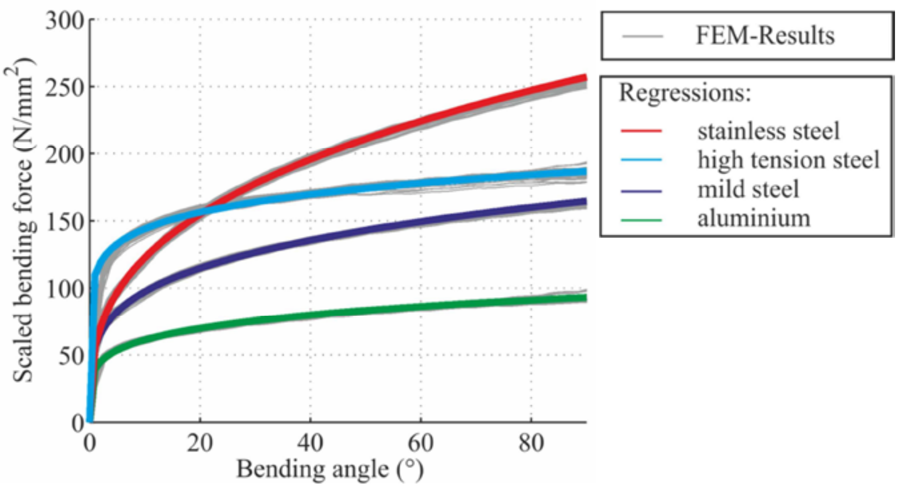

Figure 7: Scaled bending force

These results are also interesting from another point of view: The bending process is a highly complex nonlinear process (large strains, nonlinear constitutive relations, complex contact). However, a very compact formulation for the bending force is found as shown in Figure 7, when working in a proper non-dimensional formulation. This will be discussed in detail in future contributions.

6 CONCLUSIONS

In this paper, the influence of material behavior in a sheet bending process has been investigated. Especially the influence of the flow range and anisotropy have been studied. The first effect can be neglected for large bending angles. On the other hand anisotropy has to be considered appropriately in order to satisfy the high precision requirements in modern manufacturing processes. It has been shown that the flow curve can be approximated by the Ludwik equation with high accuracy if bending angles become larger. It has also been turned out that the flow-curve shows a saturation of the Cauchy stress at a specific strain larger than uniform elongation. The presented simulation results have been compared to measurement results showing a very good coincidence.

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